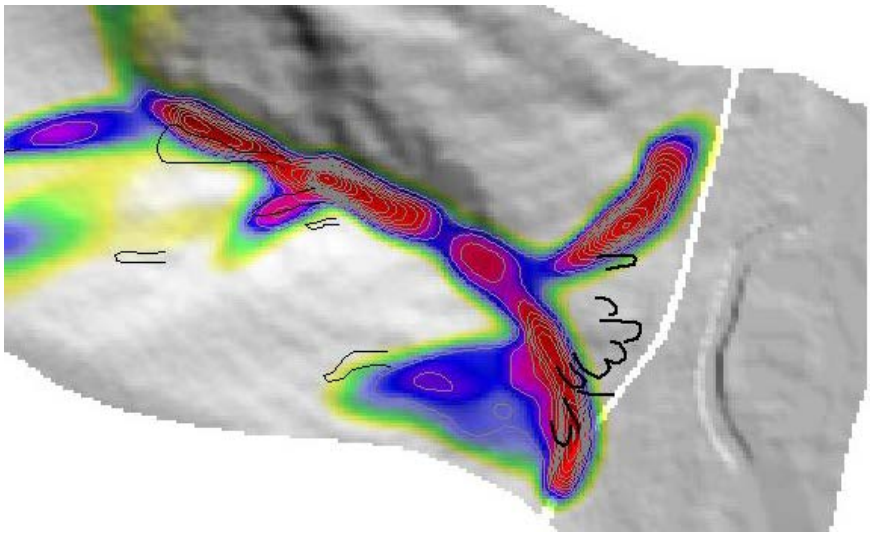
r.avalanche

Version 2012-02-08

A model for simulating the motion of granular flows (debris flows and snow avalanches)

based on GRASS GIS



User manual and model outline

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r.avalanche is a GIS-supported model framework for simulating the motion of granular flows like debris flows or snow avalanches over inclined surfaces. *r.avalanche* is designed as raster module for the software *GRASS GIS*. The scientific concepts behind *r.avalanche* are summarized in Chapter 1 (Model outline).

In contrast to most of the other *GRASS* raster modules, management of the data and the parameters (input and output) is not done by adding parameters to the *r.avalanche* command, but by an additional shell script (*r.avalanche.sh*) with various functionalities, including input of data and parameters as well as post-processing and display of the results. Instructions how to operate the model framework are given in Chapter 2 (User's manual).

The model shows a large potential for refinements. Chapter 3 (Prospected improvements) will give a short overview of ongoing and prospected further development of *r.avalanche*, regarding the scientific concepts behind it as well as its ease of use.

Every user is encouraged to report encountered bugs or errors to

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Furthermore, the developer would be grateful for receiving comments regarding

- experiences with the program, shortcomings, recommendations for improvements (scientific concepts, ease of use);
- parameters chosen for certain study areas;
- interest in cooperation with application and further development.

The model, as applicable with *GRASS*, is running under the *GNU General Public License* (www.gnu.org). *r.avalanche* has been created with the purpose to be useful for modelling of debris flows. It has been developed with care, and much emphasis has been put on ensuring its scientific value. Nevertheless, every user has to be aware that it is only a computer program created by a human being, which may contain technical and topical errors and shortcomings. No responsibility can be taken by the developer for any types of deficiencies in the program or in this document, or for the consequences of such deficiencies.

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1 Model outline

1.1 General aspects

r.avalanche constitutes a fully deterministic model for the motion of granular flows (suitable for debris flows, flow avalanches, and other types of movements). The model builds on a solution of the Savage-Hutter (SH) model for simple concave topographies with an only vertically curved flow line, running out into a horizontal plane (Wang et al. 2004; Figure 1). This means that *r.avalanche* is only suitable for relatively simple terrain with straight channels. Future development, however, shall be directed towards overcoming this problem (compare Chapter 3).

A curvilinear coordinate system is used instead of a simple rectangular system (compare Figure 1).

1.2 Model layout

r.avalanche requires far less input than *r.debrisflow* as it only simulates one part of the process. In contrast, the mathematical-technical concept behind *r.avalanche* is much more complex. A full description of the way how the SH model was solved for this specific topographic situation would go beyond the scope of this study – a detailed description is given by Wang et al. (2004). The most fundamental aspects are summarized below.

Eq. 1 to 3 are the basis of the SH model:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(hu)+\frac{\partial}{\partial y}(hv)=0 \qquad \text{Eq. 1,}$$

$$\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}\left(hu^2\right)+\frac{\partial}{\partial y}(huv)=hs_x-\frac{\partial}{\partial x}\left(\frac{\beta_x h^2}{2}\right),$$

Eq. 2 top Eq. 3 bottom

$$\frac{\partial}{\partial t}(hv)+\frac{\partial}{\partial x}(huv)+\frac{\partial}{\partial y}\left(hv^2\right)=hs_y-\frac{\partial}{\partial y}\left(\frac{\beta_y h^2}{2}\right).$$

h is the avalanche thickness, and u and v are the depth-averaged downslope and cross-slope velocities. s_x and s_y are the net driving accelerations:

$$s_x=\sin\varsigma-\frac{u}{\sqrt{u^2+v^2}}\tan\delta(\cos\varsigma+\lambda\kappa u^2)-\varepsilon\cos\varsigma\frac{\partial b}{\partial x},$$

Eq. 4 top Eq. 5 bottom

$$s_y=-\frac{u}{\sqrt{u^2+v^2}}\tan\delta(\cos\varsigma+\lambda\kappa u^2)-\varepsilon\cos\varsigma\frac{\partial b}{\partial y},$$

where ζ is the downslope inclination angle of the reference surface, $\varkappa$ is the local curvature of the reference surface, b is the elevation above the reference surface, and ε and λ are factors (compare below). β_x and β_y are defined as

$$\beta_x=\varepsilon\cos\varsigma K_x \qquad \text{Eq. 6,}$$

$$\beta_y=\varepsilon\cos\varsigma K_y \qquad \text{Eq. 7.}$$

K_x and K_y are the earth pressure coefficients in downslope and cross-slope directions.

$$K_{x,act/pass}=2\left(1\mp\sqrt{1-\cos^2\varphi/\cos^2\delta}\right)\sec^2\varphi-1,$$

Eq. 8 top Eq. 9 bottom

$$K_{y,act/pass}=\frac{1}{2}\left(K_x+1\mp\sqrt{(K_x-1)^2+4\tan^2\delta}\right).$$

φ is the angle of internal friction, and δ is the bed friction angle. Active stress rates (subscript *act*) are connected to dilatation of the material, passive stress rates are connected to compression – it depends on acceleration or deceleration of the flow whether active or passive stress rates are valid (compare Wang et al. 2004). Eq. 8 and 9 are only valid as long as the flow moves predominantly in downslope direction.

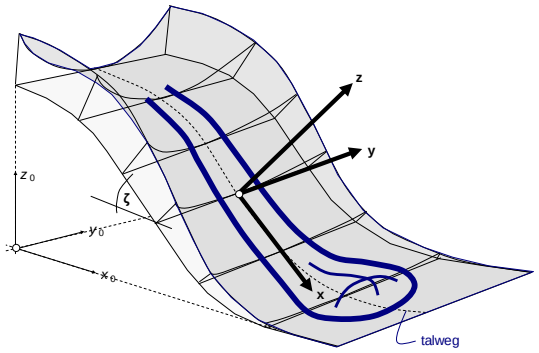

Figure 1: The topography for which the solution of the SH model used in *r.avalanche* was elaborated (adapted from Wang et al. 2004)

The system of equations described above is only valid for cohesionless and incompressible granular materials which can be considered as fluid continuum. It has to be emphasized that all variables are dimensionless, meaning that the model is scale-invariant and small-scale laboratory tests can be used as reference for large-scale problems in nature.

The differential equations Eq. 1 to 3 were solved using a NOC (Non-Oscillatory Central Differencing) scheme, a numerical scheme useful to avoid unphysical numerical oscillations. Cell averages are computed

using a staggered grid, meaning that the system is moved half of the cell size with every time step (the values at the corners of the cells and in the middle of the cells are computed alternatively). The numerical scheme derived by Wang et al. (2004) was used for *r.avalanche*.

The degree of diffusion of the flow material is governed by using slope limiters, restricting the gradients of flow depth to a certain range. The so-called minmod limiter has already been used by Wang et al. (2004) and also for the present study since it is known as the most diffusive one, reducing numerical oscillations.

The simulation is run for a number of time steps until a certain break condition is fulfilled. The time steps have to be kept short enough to fulfil the CFL (Courant-Friedrichs-Levy) condition required for obtaining smooth solutions:

$$CFL_x = \max_{alli,j} \frac{|u_{i,j}| + \sqrt{(\beta_x)_{i,j} h_{i,j}}}{\Delta x_i} \quad \text{Eq. 10,}$$

$$CFL_y = \frac{\max_{alli,j} \left[|v_{i,j}| + \sqrt{(\beta_y)_{i,j} h_{i,j}} \right]}{\Delta y} \quad \text{Eq. 11,}$$

where Δx and Δy are the cell sizes in x and y direction and i and j are the coordinates of the cells in x and y direction, respectively. The length of one time step Δt has to be smaller than 0.5 times the minimum from CFL_x and CFL_y. Δt is determined dynamically while running *r.avalanche*, based on the CFL condition from the previous time step. Instead of 0.5, a factor of 0.2 was chosen in order to add some tolerance.

1.3 Implementation into GRASS GIS

The implementation of the SH model and its solution by Wang et al. (2004) into GIS bears two problems:

(1) the solution provides dimensionless values – in the GIS, however, it is necessary to use dimensional values;

(2) the solution is valid for a curvilinear reference system only, in contrast to a GIS which usually uses a simple rectangular system.

1.3.1 Dimensionalization of the variables

The first problem was solved using equations from Pudasaini (2003). They are based on the variables L, H, and R (compare Table 1). L is the typical avalanche length, H is the typical avalanche depth, and R is the typical radius of curvature (all in meters). Dimensional variables are derived using

$\hat{x} = Lx$ Eq. 12, $\hat{y} = Ly$ Eq. 13,

$\hat{h} = Lh$ Eq. 14, $\hat{u} = u\sqrt{gL}$ Eq. 15,

$\hat{v} = v\sqrt{gL}$ Eq. 16, $\hat{t} = t\sqrt{L/g}$ Eq. 17,

$\hat{\kappa} = R\kappa$ Eq. 18,

where the variables denoted with a cap are the dimensional counterparts of the variables discussed above and g is gravitational acceleration (9.81 m s^{-2} on the earth surface). *r.avalanche* proved to work best when setting x, y, and h to the dimensional values (in m) while setting L, H, and R to 1. The factors $\varepsilon = L/H$ and $\lambda = L/R$ (Pudasaini 2003) were therefore 1. This contradicts the statement by Wang et al. (2004) that the factors should be far lower than 1, but appears appropriate when using dimensional values from the beginning with h being much smaller than the length of the flow.

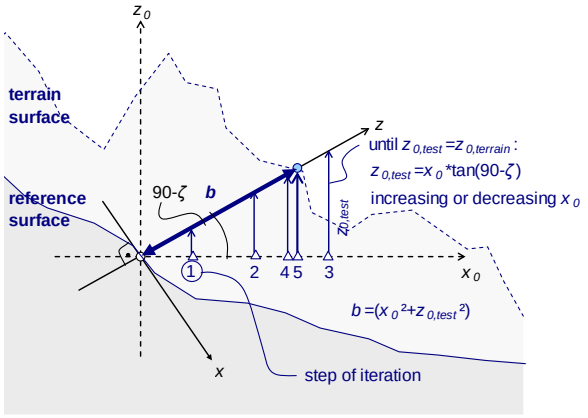

Figure 2: Iterative determination of *b* based on the coordinate system defined by the reference plane. Designed by M. Mergili.

1.3.2 Adaptation of the coordinate system

The solution of Wang et al. (2004) builds on a curvilinear coordinate system based on a horizontally straight "talweg" which shall be the predominant flow direction. Three steps are performed for converting the original rectangular coordinate system in which the input raster maps are provided into the coordinate system for the simulation:

(1) the coordinate system is rotated around the $\tilde{z}$ axis so that the expected predominant flow direction derived from the starting material and the elevation model is aligned with the new x direction. This rotation is based on two user-defined pairs of coordinates in the flow channel (compare Table 1);

(2) a reference surface is created, based on the defined "talweg" and an inclination of zero in y (cross-slope) direction;

(3) based on this reference surface, the cell size Δx for each x parallel to the reference surface is computed. The elevation h (m) – defined as the distance between terrain surface and reference surface perpendicular to the reference surface – is derived. This has to be done iteratively, varying the horizontal shift until the tested value of h converges with terrain height (Figure 2).

After completing the calculation, the entire system is reconverted into the rectangular coordinate system

used in the current GRASS GIS mapset in order to enable a proper display of the results.

1.4 Acknowledgements

Funding was provided by the Tyrolean Science Funds, the Vice Rector for Research of the University of Innsbruck ("Doktoratsstipendium aus der Nachwuchsförderung der LFU"), and the Austrian Academy of Sciences.

Furthermore, the valuable remarks of Wolfgang Fellin (Institute of Infrastructure, University of Innsbruck), Katharina Schratz, and Alexander Ostermann (Institute of Mathematics, University of Innsbruck) are acknowledged.

1.5 References

Pudasaini, S.P. 2003: Dynamics of Flow Avalanches Over Curved and Twisted Channels. Theory, Numerics and Experimental Validation. Dissertation at the Technical University of Darmstadt, Germany. 200 pp.

Wang, Y.; Hutter, K.; Pudasaini, S.P. (2004): The Savage-Hutter theory: A system of partial differential equations for avalanche flows of snow, debris, and mud. *ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift für Angewandte Mathematik und Mechanik* 84:507-527

Table 1: Input information required for running *r.avalanche*.

map/parameter	symbol (unit)	input format	description
catchment	– (boolean)	raster map	catchment of interest map
elev	z (m)	raster map	elevation map
delta	δ (degree)	raster map	basal angle of friction map
riskobj	– (boolean)	raster map	objects at risk (1 = present, 0 = absent)
dinit	h_0 (m)	raster map	starting material map
phi	φ (degree)	value	angle of internal friction of the debris flow material
L	L (m)	value	typical avalanche length (recommended: 1; compare text)
H	H (m)	value	typical avalanche depth (recommended: 1; compare text)
R	R (m)	value	typical radius of curvature (recommended: 1; compare text)
deltatout	Δt_{out} (s)	value	interval between writing output
tmax	t_{max} (s)	value	time of simulation until it stops
vmin	v_{min} (m s^{-1})	value	velocity at maximum flow depth at which simulation stops
xchan1, ychan1	– (m)	values	coordinates of first point in flow channel (for rotating coordinate system)
xchan2, ychan2	– (m)	values	coordinates of second pt. in flow channel (for rotating coordinate system)

2 User's manual

2.1 System requirements

r.avalanche was developed and tested under *Fedora Core 6* with *GRASS 6.2.1*. It probably works on most other *UNIX* systems as well as with other versions of *GRASS*. The module itself should also be usable under *cygwin*, but the related shell script *r.avalanche.sh* (compare below) would probably not work.

Please make sure to have a proper installation of *GRASS* before installing *r.avalanche*. In case of doubt, please consult www.grass.itc.it.

2.2 Test dataset

A test dataset is provided together with the program, consisting of some text files and a *GRASS* location with the name *test_ravalanche*. All data is packed in the file *test_ravalanche.zip*.

Table 2 shows the names of the raster and vector maps. The test dataset is suitable to run *r.avalanche* at spatial resolutions of 5 m or 10 m.

Table 2: Names of the maps of the test dataset

name of the map	description
test_mask	mask for study area (raster)
test_elev	elevation map at 5 m resolution (raster)
test_elev10	elevation map at 10 m resolution
test_delta	bed friction angle (raster)
test_road	road potentially at risk (raster)
test_dinitdef	depth of flow initiation (raster)
test_init_observed	observed patterns of flow initiation (line vector)
test_depd_observed	observed patterns of deposit from flow (line vector)

2.3 File management

The file system *r.avalanche* consists of two parts:

- a *GRASS* mapset with all the spatially distributed input information as raster or vector maps, and
- a folder named *r.avalanche* which may be stored at any location of your `home` directory. The internal structure of the folder *r.avalanche* may not be manipulated, otherwise the functionalities are not more given.

The directory *r.avalanche* contains the following subdirectories:

`tools`

The `tools` directory hosts the scripts required for installing and running *r.avalanche*:

- *main.c*: the source code for *r.avalanche*;
- *r.avalanche.sh*: a shell script facilitating data input, management, and output;
- and *install.sh*: a shell script helping to compile the source code (*main.c*).

`data`

It contains the parameter file (*test_param.txt* as part of the test dataset). The subfolder `/colors` contains colour tables for the display of the results.

`temp`

The `temp` directory contains temporary files created during the execution of *r.avalanche.sh*. Its content shall not be manipulated manually, but only using the functionalities of *r.avalanche.sh*.

`results`

It contains some simulation results (summary file, profile file). However, the main results are stored as rasters in the active *GRASS* mapset.

`docs`

The `docs` directory contains this manual.

2.4 Installation

r.avalanche has to be added to the *GRASS* raster library as a new module, based on the source code of the file *main.c*. For performing this task, call the script *install.sh* in the folder `r.avalanche/tools`:

```
cd dir/r.avalanche/tools
sh install.sh
```

`dir` may be any location in your `home` directory. The following prompt is displayed:

```
Full path to GRASS source (slashes at be-
ginning and end):
```

Here, enter the path to the *GRASS* source, for example

```
/usr/local/src/grass64_release/
```

The Makefile is created, and compilation and installation are run automatically, so that *r.avalanche* is ready to use.

Please note that you have to change to the tools directory as described above – if just entering

```
sh dir/r.avalanche/tools/install.sh
```

an error message will display and *r.avalanche* will not be installed.

2.5 Data management

r.avalanche uses text files and rasters with predefined names as input. The shell script *r.avalanche.sh* serves for creating these datasets.

r.avalanche.sh offers the following modules:

```
1 --> Parameter and data input
2 --> Execution of simulations
3 --> Post-processing of model output
4 --> Display of results
5 --> Removal of result files
6 --> Cleaning of file system
7 --> Exit
```

When entering a number, the corresponding module is executed. *r.avalanche.sh* has to be called from within the *GRASS* mapset with all the required raster maps.

2.5.1 Parameter and data input

Module 1 consists of a sequence of prompts for input of data and parameters (Table 1). If no input is given for a prompt (by just pressing *ENTER*), the dataset specified earlier is kept.

- `--> Catchment map (boolean):`

  Boolean raster map defining the catchment of interest (identified by cell values of *1*, areas out of the catchment are defined by *0* or *no data*).

- `--> Elevation map (m):`

  Raster map of elevation (meters).

- `--> Bed friction angle map:`

  Raster map of bed friction angle (decimal degrees).

- `--> Objects at risk map (boolean):`

  Boolean raster map denoting objects at risk (*1* for presence of potential objects at risk like roads or buildings, else *0* or *no data*).

- `--> Estimated depth of mobilization of soil map (m):`

  Raster map showing the patterns of estimated initiation of the debris flow or snow avalanche (depth in meters).

- `--> Parameter file:`

  File with list of parameters for the simulation. The parameters have to be specified in a defined order (compare Table 1 and *test_param.txt*).

2.5.2 Execution of simulations

A prompt for cell size displays:

```
--> Cell size (m):
```

The cell size has to be chosen in accordance with the input datasets and the required level of detail. For test simulations it is recommended to choose larger cell sizes in order to reduce computing time. However, results have shown that the chosen cell size may have a considerable influence on the simulation results.

After specifying the cell size, the *GRASS* raster module *r.avalanche* is called by pressing *ENTER*. Additionally to an array of raster maps, a summary file (*summary.txt*) and a profile file (*profile.txt*) are written and stored in the

```
dir/r.avalanche/results/
```

directory. The summary file contains some variables (time step length, maximum depth and velocity of the flow, and flow volume) for each time step. The profile file contains a profile of flow depth along the predefined flow channel for each time step.

Please note that if you wish to run *r.avalanche* manually, not from within *r.avalanche.sh*, you have to copy the parameter file to the `dir/r.avalanche/temp/` directory as *param.txt*. This file shall not contain labels, but only the values.

2.5.3 Post-processing of model output

All the resulting raster maps are cleaned (cells outside of the defined catchment are set to no data) and a color table is assigned to the flow depth map for each time step. The colour tables are stored in `dir/r.avalanche/data`.

Furthermore, three prompts do appear when calling the module. Each task is accepted by typing *1*, or denied by typing *0*.

- `--> Maximum flow depth for display (cm):`

  The flow depth which should serve as maximum for colouring the maps to be displayed (compare below) has to be specified in full centimetres.

- `--> Interval of contour lines for display (m):`

  Contour lines of flow depth (not of ground elevation!) are shown on the maps during display (compare below). The interval between these contours has to be specified here.

- `--> Export maps to ascii (boolean) ?`

  If *1* is entered, the resulting raster maps are exported as ascii rasters in order to be usable with other GIS software products. The resulting files are stored in `dir/r.avalanche /results/asc`. Please enter *0* if you do not wish to export the maps.

In the output rasters, the displays during program execution, and in the summary and documentation files, every variable is addressed by a shortcut (Table 3). The names of the resulting raster maps have the prefix *r_*. The number at the end of the raster map names indicates the time step. For example, the raster *r_dflow0020* shows the flow depth at the end of time step 20. Attention: These time steps are different from those used for the computation itself (compare Chapter 1).

2.5.4 Display of results

A sequence of flow depth maps over all time steps can be displayed using this module. The following parameters have to be specified:

- `--> Azimuth of the sun for shaded relief map:`

  All maps are displayed with a shaded relief as background, the azimuth of which has to be specified (in decimal degrees; recommended for most areas: 315).

- `--> Interval for export of maps to jpg:`

  The displayed maps can be automatically stored as `jpg` graphics in `dir/r.avalanche/results/jpg`. If you wish to do so, please specify an integer number larger than ***0***, else ***0***. The number you enter defines the interval of output – for example, if you enter ***4***, the map from every 4th time step is exported.

- `--> Height of monitor in pixels:`

  Please specify the height of the monitor for display – a value between 500 and 800 is recommended, depending on the size of your monitor.

- `--> Observed patterns of debris flow initiation (line vector):`

  A line vector map with areas of debris flow initiation observed in the field may be specified, if available, for facilitating the evaluation of the model results.

--> Observed patterns of debris flow deposition (line vector):

A line vector map with areas of debris flow deposits observed in the field may be specified, if available, for facilitating evaluation of the model results.

A monitor opens, and a prompt with instructions appears in the terminal. The maps are displayed in a defined sequence (over all time steps forward) – please enter the number of steps to move forward or backward, or ***exit*** to quit. If you have moved a defined number of steps fore- or backwards and would like to apply the same action again, you can just press ***ENTER*** to do so.

If you have chosen to export the maps as `jpg`, no prompts appear, but all maps are displayed and exported automatically.

Please note that the size of the monitor and the placement of some of the elements of the maps (legend, bar scale) are not suitable for all map formats. It may happen that some of the placement options have to be changed in the shell script ***r.avalanche*** itself in order to design satisfactory layouts.

The text on the display is partly copied from the `summary.txt` file in the `dir/r.avalanche/results/` directory – please do not rename or remove this file before the display of the maps is completed.

2.5.5 Removal of result files

All results (rasters and text files produced by ***r.avalanche*** and Module ***3***) are deleted. All temporary files created in ***Module 1*** are kept, so that new simulations may be performed immediately.

2.5.6 Cleaning of file system

All temporary rasters and text files created in ***Module 1*** are deleted. ***Module 1*** must be re-run in order to perform new simulations.

2.5.7 Exit

r.avalanche.sh is exited and the default cell size is restored

Table 3: Output from ***r.avalanche*** (after running Module 4). r=raster map, s=summary file, p=profile file

shortcut	description	unit	versions			time steps
			r	s	p	
dflow	flow depth	m	x		x	all
vx	flow velocity in x direction	$m\ s^{-1}$	x			all
vy	flow velocity in y direction	$m\ s^{-1}$	x			all
dflow_max	maximum flow depth over all time steps	m	x			–
hmax	maximum flow depth over all cells	m		x		all
vmax	maximum flow velocity over all cells	$m\ s^{-1}$		x		all
vol	flow volume	m^3		x		all
vol_riskobj	flow volume on object at risk (road, etc.)	m^3		x		all
deltat	length of time step	s		x		all
tsum	time elapsed since start of simulation	s		x		all
cfl	Courant-Friedrichs-Levy condition (comp. Chapter 1)	–		x		all

3 Prospected improvements

3.1 Scientific concepts

This document describes Version 1.1 of *r.avalanche*. It constitutes a first try to implement a fully deterministic model for the motion of granular flows into Open Source GIS. Therefore it has been kept relatively simple and shows some limitations. It is planned to improve the model by the following steps:

(1) to select and adapt a sound method for modelling rapid granular flows over arbitrary topography, in order to overcome the severe limitation that the model can only be applied for relatively simple topographies. The method shall be extended by incorporating particle entrainment, which can have important implications for the runout behaviour of granular flows, and and the role of pore fluid. The differential formulation of the model shall be derived analytically, using and extending the existing theories;

(2) to devise an appropriate numerical scheme (including shock capturing) for solving the equations derived in (1). Numerical solutions of the analytical model for arbitrary topography shall be elaborated and implemented into *GRASS GIS*, analogous to the present version of *r.avalanche*;

(3) and to evaluate the quality of the developed approach by comparing it to existing methods and models (*DAN*, *SAMOS*) and to validate the results with data from past snow avalanches and debris flows.

An additional improvement would be to find a more efficient way of data management during the computation in order to decrease computing time and to facilitate computations at higher spatial resolutions.

3.2 Ease of use

One of the next steps shall be to improve the quality of display of the results (*Module 4* of *r.avalanche.sh*).

In its current version, the operation of *r.avalanche* runs very much on text files and the command line. For the future it would be desirable to have a graphical user interface facilitating data management and at least partly replacing *r.avalanche.sh*.